FARWELL

An investigation of a special case of rotary converter hunting

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AN INVESTIGATION OF A SPECIAL CASE OF ROTARY CONVERTER HUNTING

BY

STANLEY PRINCE FARWELL

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I HEREBY RECOMMEND THAT THE THESIS PREPARED UNDER MY SUPERVISION BY

Mr S. P. Farwell

ENTITLED An investigation of a special case of Rotary Converter hunting

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Committee on Final Examination

-TABLE OF CONTENTS-

Curves and Diagrams

-INTRODUCTION-

The rotary converter from which the data for this thesis was obtained is installed in the dynamo laboratory of Central University of Kentucky, Danville, Ky. A copy of the nameplate is given below:-

WESTINGHOUSE

ELECTRIC & MFG. CO. PITTSBURG, PA.,U.S.A.

Rotary Converter

7.5 KW	125 D.C. Volts	60 D.C. Amps.
2 Phase	60 Cycles	1800 R.P.M.

Serial No. 672043

Power was supplied to the converter from two 5 K.V.A. Westinghouse type S transformers with primaries connected to the 2000 volt lines of the local lighting plant. Taps were provided on the secondaries whereby a secondary voltage of 87 volts could be obtained for operation of the converter, thus giving a ratio of 23 : 1 for the transformer.

The transmission lines were found to have the following characteristics:-

Phase	Size Wire	Length	Resistance	Reactance	Impedance
A	#6	8040 ft.	6.35 ohms	1.94 ohms	6.63 ohms
B	#6	5320 "	4.20 "	1.28 "	4.39 "

The inequality in length of the transmission lines could not be avoided, on account of the existing layout of the town circuits,

The converter is adapted for starting from the alternating end by having a field break-up switch splitting the field into two parts. The procedure in starting is as follows:-(1) With the break-up switch open, full A.C. voltage is impressed on the A.C. rings(2) When the machine is up to synchronous speed, as judged by the ear, the break-up switch is closed and the machine operates as a synchronous converter(3) The field excitation is then adjusted for minimum line current. It should be here noted that the field has a simple shunt winding and the converter is self-excited.

When the converter is thrown into service, it does not run steadily but there are rapid periodic fluctuations in its speed, indicated by beats easily audible. At the same time, the ammeters in the two phases show an abnormal, fluctuating current as flowing in each phase. The voltmeters giving the impressed pressure fluctuate somewhat but to no where near the extent that the ammeters do. Wattmeters in each phase show the power input to vary to a great extent. In fact, the movement of the wattmeter needles is so violent that it is almost impossible to obtain an idea of the power input. Since these readings are very erratic, they are practically worthless for use in calculations and no weight is placed upon them in this thesis.

The phenomenon above described is known variously as "hunting", "pumping", or "surging". On the following pages will be found a discussion of those facts in connection with the phenomenon of hunting which are pertinent to the case in hand. For much of this information, I am indebted to Dr.C.P.Steinmetz, writing in his "General Lectures on Electrical Engineering" and "The Theory and Calculation of Alternating Current Phenomena".

-THE HUNTING OF SYNCHRONOUS MACHINES-

The state of affairs which exists when a synchronous motor or converter is connected to a source of power is shown in Fig.1. Here e_0 is the impressed E.M.F., e is the counter E.M.F. of the converter and the resultant E.M.F. acting to send current thru the machine is the vector difference between e_0 and e, given both in phase and amount by the line joining the ends of the vectors. The current I produced in the motor armature lags behind the E.M.F. producing it by the angle α, whose value $= \tan^{-1} x/r$, where x is the reactance of the circuit between e_0 and e, and r is its resistance. The angle of phase difference between the impressed and counter E.M.F's is denoted by β. This diagram shows normal conditions of operation.

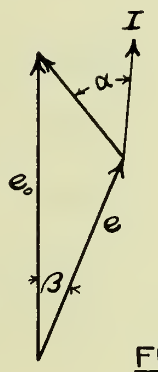


FIG. I

Ordinarily, when two machines are thrown together out of phase, or are brought out of the phase by some cause (as the beat of an engine), they pull each other in phase again, oscillate against one another a few times and gradually assume a fixed phase relation to each other as the oscillation decreases and dies out. Then, with a given power output and values of e_0 and e, the machine runs steadily and the angle β is constant.

Hunting is a continued oscillation. The causes of this phenomenon may be one or more of the following:-

-CAUSES OF HUNTING-

(1) Magnetic lag

(2) Pulsation of engine speed

(3) Hunting of engine governors

(4) Wrong speed characteristic of engine

(1) When the machines move apart, the magnetic attraction opposes separation. When they pull together again, magnetic attraction pushes them together with the same force, so that they would move over the position of coincidence in phase and separate again in the opposite direction as much as before. Energy losses, as friction, etc., retard the separation and so make them separate less than before, every time they do, so that the oscillation is gradually stopped. If, however, there is a lag in the magnetic attraction, they come together with greater force than they separated, so they separate farther in the opposite direction and the oscillation increases until the machines fall out of step or the increasing energy losses stop the increase. This kind of hunting is stopped by increasing the energy losses due to the oscillation, by copper bridges between the poles, by aluminum collars around the pole-faces or by a complete squirrel-cage winding in the pole-faces.

The frequency of hunting depends on the magnetic attraction, that is, on the field excitation, and on the weight of the rotating mass. The higher the field excitation, the greater the magnetic force, that is, the quicker the motion of the machine and therefore the higher the frequency. The greater the weight,

the slower it is set in motion, that is, the lower the frequency. Characteristic of this hunting, therefore, is that its frequency is changed by changing the field excitation.

(2) If the speed of the engine varies during the rotation, rising and falling with the steam impulses, then the speed of the alternator and hence the frequency, pulsate with a speed equal to, or a multiple of , the engine speed. The synchronizing current which holds the converter in step with the system, tends to cause the converter to follow any irregularity in the frequency of the supply current. Therefore there is produced by the generator irregularity a relative oscillation of phase between the two machines. The periodic hunting of the engine governor, the steam admissions, the momentum of the reciprocating parts, the inertia of the generator armature and that of the converter armature, are elements which tend to increase or diminish this oscillation. Periodic phase shifting may be counteracted by flywheel effect for the converter, magnetically weak armature compared to field, or damping devices. As the armature oscillates back and forth across its normal position, the shifting armature magnetism produced by the unconverted portion of the current, induces current in the low resistance copper dampers, which current always opposes the magnetism which produces it. The damping action thus brought into play when the field is suddenly distorted has the effect of suppressing the oscillations. When the alternations of the supply are irregular, the damping devices act to cause the converter to follow the irregularities, but prevent an exaggeration of the momentary phase displacement of the armature and thus have a

steadying effect upon the whole system.

If the frequency of oscillation of the machine as determined by its field excitation and the weight of its moving part is the same as the frequency of the engine impulses, that is, the same as the number of engine revolutions or a multiple thereof, then successive engine impulses will always come at the same point of the machine beat and so continuously increase it: that is, the machine oscillation increases, or the machine hunts. In this case of cumulative hunting caused by the engine impulses, the frequency of oscillation agrees with the engine oscillation.

(3) and (4) are causes of hunting not present when, as in this case, a single alternator is in service.

-STEINMETZ FORMULA FOR FREQUENCY OF HUNTING-

Dr. Steinmetz in the chapter on "Surging of Synchronous Motors" in his "Theory and Calculation of Alternating Current Phenomena" treats mathematically the surging of synchronous motors, considering a periodic variation of phase between the impressed and counter E.M.F's. Since synchronous motors and converters have essentially the same characteristic performance when the converter is running without D.C. load, any conclusions of Dr. Steinmetz regarding motors are also applicable to converters. Accompanying a phase shifting of $\underline{e}_0$ and $\underline{e}$, set up from any cause whatsoever, there is an accelerating and decelerating action on the armature and corresponding variations in the power consumed, as energy is spent in increasing momentum or returned by decreasing momentum. These fluctuations of power and speed and current have an ampli-

tude and period depending upon the circuit conditions and upon the mechanical momentum. If the amplitude of this pulsation has a positive decrement, that is, is decreasing, the machine assumes after a while a constant position of $\underline{e}$ regarding $\underline{e_0}$, that is, its speed becomes uniform. If, however, this decrement is negative, an infinitely small pulsation will continuously increase in amplitude, until the motor is thrown out of step, or the decrement becomes zero, by the power consumed by forces opposing the pulsation, as anti-surging devices, or by the periodic pulsation of the synchronous reactance. If the decrement is zero, a pulsation once started will continue indefinitely at constant amplitude. The following formula is derived by Dr. Steinmetz for this last case where the machine is in stable equilibrium, when oscillating with a constant amplitude β, depending upon the initial conditions of oscillation, and a period f_0. The oscillations are assumed to be small.

$$f_0 = \sqrt{\frac{fee_0 \sin(\alpha - \beta)}{4\pi z M_0}}$$

where

f = frequency of generator

e_0 = impressed E.M.F.

e = counter E.M.F.

α = angle of lag of current behind resultant E.M.F.

β = phase angle between e and e_0

z = impedance of circuit between e and e_0

M_0 = mean mechanical momentum, in joules

$\underline{M_0}$ in the above expression $= \frac{1}{2}mv_0$, where v_0 is the mean linear velocity of the machine at the radius of gyration and

$\underline{m}$ is the mass of the rotating part, in engineers' units.

This formula applies only in cases where no damping or anti-surging devices are used. For a more complete discussion of this subject, it is necessary to introduce under the radical sign the term

$$-\frac{(c^2 + pP_o - h^2)^2}{64\pi^2 M_o^2}$$

In this term, c^2 is the power which would be required to drive the magnetic field of the machine thru the circuits of any anti-surging device at full frequency, if the same relative proportions could be retained at full frequency as at the frequency of slip s. The mechanical power consumed by the load varies more or less with the speed; approximately proportional to the speed if the machine drives mechanical apparatus, or at a higher power of speed if driving D.C. generators or running as a synchronous converter. Calling P_o the power developed by the machine, and assuming that the mechanical power varies as the "p"th power of the speed, it is found by the appropriate calculations that these factors enter into the expression in the manner given above.

The term $-h^2$ enters into the expression thru a consideration of a power $P_2 = -h^2 s$, representing a retarding torque during slow speed, or increasing β, and an accelerating torque during high speed, or decreasing β. The source of this power may be found external to the motor, or internal, in its magnetic circuit. An internal cause of a negative term P_2 is found in the lag of the converter field behind the resultant magnetomotive force. $\underline{e}$ is "nominal generated E.M.F." corresponding to the field excitation. The actual magnetic flux of the machine does not correspond to $\underline{e}$

and thus to the field excitation, but corresponds to the resultant magnetomotive force of the field excitation and the armature reaction, which latter varies in intensity and in phase during the oscillation of β. Hence, while $\underline{e}$ is constant, the magnetic flux is not constant, but pulsates with the oscillations of the machine. In self-exciting synchronous converters, the pulsation of $\underline{e}$ is intensified by the pulsation of direct current voltage caused thereby, and hence of excitation.

If the term $\underline{h}^2$ be not present, a cumulative surging, or one with continuously increasing amplitude, cannot occur. The machine when displaced in phase from its mean position, either returns thereto aperiodically, or with an oscillation of vanishing amplitude or, at the worst, it may oscillate with constant amplitude. But if there be present a cause for a term h^2, such as a magnetic lag, then the machine oscillates with constantly increasing amplitude, until it drops out of step or the increasing energy losses, represented by c^2 and pP_o, stop the increase.

The avoidance of surging thus requires:

(1) An elimination of the term h^2, or reduction as far as possible.

(2) A sufficiently large term c^2 or

(3) A sufficiently large term pP_o.

(1) Refers to the design of the machine and the system on which it operates.

(2) Leads to the use of electromagnetic anti-surging devices, as a squirrel-cage winding in the field poles, short circuits between the poles, or around the poles.

(3) Leads to flexible connection to a load or a momentum, as flexible connection with a flywheel, or belt drive of the load.

-GENERATORS AND ENGINES-

The generating equipment at the Danville power plant is composed of two exactly similar generating sets. But one set is run during the day and all tests on the converter were made then. ENGINES:-"Ideal", made by A.L.Ide & Co., Springfield, Ill. The cylinders are 14" x 16". These engines are provided with a heavy pulley and a flywheel and are direct-connected to the generators. GENERATORS:- Are of General Electric Co. manufacture. Type AQB. Class 28 - 105 A - 257. Form E. Volts 2300. Amp. 23. Speed 257. The resistance per phase (two phases) was found to be 2.03 ohms and the synchronous impedance 57 ohms. The excitation was supplied from a small 125 volt D.C. generator mounted upon the main engine and generator shaft. The exciter voltage was found to have about an half a volt variation and it was assumed from this fact that there was about .4 of 1 per cent variation in the angular velocity of the engine during each revolution. The irregularity factor for a load comprising synchronous converters is generally not allowed to one-half of one per cent, according to the"Standard Handbook for Electrical Engineers". In this generator, there are 14 cycles per revolution, and one cycle corresponds to to a displacement of the flywheel of 25.7°. Supposing that the prime mover swings 2° which is the usual maximum allowance, there would be a phase swing of $\frac{2}{25.7}$ or 7.8 per cent of a period, which means a phase swing of 28° in the electric circuit. In other words, the vector e oscillates thru an angle of 28°. Using an irregularity

of .4 per cent, the corresponding phase shift in the electric circuit is found to be 20.5°

A telephone in series with a D.C. voltmeter was connected across the terminals of the exciter of each machine while in service and it was found that the angular variation of the engines was dissimilar. Machine #1 gave a steady intermittent sound in the telephone, of a period equal to that of the engine speed and the movement of the voltmeter was very small. The small variation in angular speed was also shown by the faintness of the sound in the telephone. When the testing apparatus was connected to #2, the sound in the telephone was irregular. There was plainly to be heard the sound corresponding to the variation of the engine in each revolution. Every third pulsation was louder than the others and at the same time the voltmeter needle gave an extra large swing, amounting to .5 volt in 125, indicating an irregularity factor of .4 per cent. The speed of the engine was given as 262 by a speed indicator and the accentuated pulsations were counted as occuring at the rate of 88 per minute. An inspection of the engine disclosed a jump of the whole rotating part occuring every third revolution. This peculiar behavior is probably due to a slight bend in the shaft sustained at the time of an accident to the engine about a year ago.

The curves on sheet #1 show the wave form of the supply circuit. The waves of both phases are seen to be practically the same and are somewhat peaked. The irregular contour of the waves would indicate the presence of higher harmonics. The data for the curves was obtained by a step-by-step contact method.

Sheet #2 gives the curves taken in order to get the synchronous impedance of the generator. It was found that the impedance for the light loads on the generator when the converter was running was sensibly constant and equal to 57 ohms. The curves show that 1260 volts were required to force full load current of 23 amperes thru the short-circuited armature. In other words, the impedance ratio of the generator is 55 per cent.

-TRANSFORMER DATA-

As mentioned above, the transformers are each 5 k.v.a. type S, Westinghouse make. As a matter of interest, the following data on these transformers is quoted from Westinghouse sources:

Iron loss--------------------------------45 watts

Copper loss, full load-----------------93 watts

Exciting current, in per cent full load current = 2.3

	Full load	3/4 load	1/2 load	1/4 load
% Efficiency	97.3	97.5	97.3	96.1

The resistances of the primary and the working portion of the secondary were measured, and found to be 8.15 and .014 ohms respectively. The primary was measured by a decade bridge and the secondary by the drop of potential method.

The synchronous impedance was determined from the primary side. The observed values of voltage impressed, current produced, and calculated values of impedance are given below:-

E	I	Z
26.0	.91	28.6
42.0	1.48	28.4
52.5	1.84	28.5

Mean value of Z = 28.5

% impedance drop, full load = 3.5

-CONVERTER DATA-

The following gives the determination of the resistance of the two phases of the converter by the drop of potential method:

Phase	E	I	R	Mean R
A	.86	8.3	.104	
	1.05	10.1	.104	.104
B	.79	8.2	.096	
	.94	10.1	.093	.095

The resistance per phase of the wires from the converter to the transformer was found by the drop of potential method to be .158 ohms and that part of the secondary circuit between the converter and the switchboard, where readings of impressed pressure and current were taken, had a resistance of .018 ohms.

Data taken for the determination of the synchronous impedance of the converter willbe found below, and also the value of the impedance, in ohms. The machine was run at synchronous speed and was separately excited. A switch was arranged so that both phases could be short-circuited, phase "A" thru an ammeter, and a voltmeter was connected to give the terminal E.M.F. of the same phase. Then the impedance was obtained by dividing the E.M.F. on open circuit by the current it produced on short-circuit.

E	I	Z	Mean Z
39.0	44.5	.876	
44.0	50.0	.880	
46.0	52.7	.873	.876

Sheet #3 shows a magnetization curve of the converter when belt-driven at synchronous speed with separate excitation. Voltage readings were taken on phase "A". Below are given the readings from which this curve was plotted:-

Readings for Magnetization Curve

Terminal volts	Field current
43.0	.72
48.0	.83
51.0	.89
56.5	1.00
66.5	1.22
74.5	1.40
79.0	1.52
82.5	1.62
85.0	1.69
90.0	1.82
94.5	1.93
97.0	2.03
104.0	2.29
107.0	2.39
114.5	2.70

Sheet #4 gives a comparison of the wave forms of the supply E.M.F., phase "B", the converter E.M.F., phase "B", and a true sine wave. The ordinates of the first two curves represent to scale the deflections of a ballistic d'Arsonval galvanometer produced by the discharge of a condenser charged to the instantaneous E.M.F. at successive points of the waves. A contact fixed to a shaft rotating synchronously with the machine producing the E.M.F. to be investigated made contact with a spring whose angular position about the shaft could be varied by equal steps. The making of this contact once each revolution, caused the condenser to be charged to whatever E.M.F. the machine was at that instant generating. No attempt has been made to plot an equivalent sine wave: it is introduced simply for comparative purposes.

An inspection of sheet #4 shows that the converter wave is very irregular, although its general shape is not far removed from that of a sine wave. Some of the peaks in this wave at first seemed due to experimental errors, but careful re-readings gave

the same results. The considerable difference between the waves of the converter and its supply circuit would act to cause cross-currents between the machines and assist, if not cause, hunting.

The moment of inertia of the armature of the converter was obtained by a torsion method. A steel rod was screwed firmly into the end of the armature shaft and the armature was suspended by the rod, whose upper end was firmly fixed. Then the armature was twisted about the vertical axis from its position of rest and the number of complete oscillations per second were determined. The oscillations with a large pulley on the shaft were also found. The weight of the armature, with and without the large pulley, was ascertained, as was also the weight of a grindstone of regular form. The rod was then fixed in the end of the grindstone shaft and the oscillations were determined as before. The moments of inertia of these bodies were then to each other directly as the squares of their times of one oscillation. The moment of inertia of the grindstone was readily calculated from the expression for the moment of inertia of a right circular cylinder, $I = 1/2\ mr^2$; where $\underline{m}$ is the mass and $\underline{r}$ the radius. Knowing $\underline{I}$ for the stone, the values for the armature were calculated. The radius of gyration of a body $= \sqrt{\frac{I}{m}}$ and the radii desired were calculated from this expression. The results are given below:-

	Mass	Moment of Inertia	Radius of Gyration
	"g-lbs"	"g-lbs"-ft.	ft.
Armature with small pulley (paper)	-4.83	.236	.221
" " large " (iron)	--6.10	.740	.348

-TESTS ON HUNTING-

As was noted above, the converter is started as an induction motor, with the fields open. The machine is allowed to come up to maximum speed and then the field circuit is closed. It was found that as soon as this was done, the converter began to hunt and this hunting increased until the machine appeared about to fall out of step. At the same time, the current thru the armature oscillated widely, with an increasing amplitude. And the movement of the needles of wattmeters in each phase was so erratic that readings could not be taken. Finally, however, the increase in the amplitude of the hunting stopped and the machine ran in stable equilibrium oscillating with an amplitude nearly constant. There were secondary oscillations which seemed to indicate the presence of superimposed frequencies. It was found that the frequency of hunting was dependent upon the field excitation: the higher the excitation, the greater the frequency. Accordingly a series of readings of power input in watts, W, current per phase, I, E.M.F. impressed, e_o, field excitation in amperes, I_f, and oscillations per minute, Osc, were taken, the excitation being varied. Values of impedance drop(= IZ)were calculated, and the counter E.M.F., e, corresponding to each value of field excitation was obtained from the magnetization curve on sheet #3. The oscillations per second were calculated from the oscillations per minute and are given in the table below under F.

For the two highest values of excitation, the amplitude of the oscillations became so great that the machine nearly fell out of step. Corresponding readings of power are very unreliable.

During this test, the converter was run without D.C. load, save that required for field excitation. The results are shown by the curve on sheet #5.

The field of the machine was much under-excited in this test. Excitations approaching normal produced unstable equilibrium and could not be used. Since the excitation was below normal, the current drawn from the line was lagging, and the power factor was very low, say .25.

Phase	I_f	e_o	I	W	Osc.	IZ	e	F
A	.58	77.5	50.0	750	168	43.8	35.3	2.80
B		77.0	57.0	940				
A	.70	79.5	50.5	750	175	44.2	41.6	2.92
B		79.0	57.5	910				
A	.80	80.2	50.6	740	180	44.3	46.7	3.00
B		80.0	57.8	920				
A	.89	80.0	51.0	720	185	44.7	51.0	3.08
B		80.0	58.0	940				
A	1.01	79.9	53.0	550	192	46.4	57.0	3.20
B		79.5	58.5	990				
A	1.16	81.5	57.7	620	200	50.5	64.0	3.34
B		81.6	60.0	1000				

Below are given the results of a test running the converter on each phase separately. These results are plotted on sheet #6. The amplitude of the oscillations was much greater for a given excitation than when both phases were in service. The variation in D.C. voltage is given as a measure of the total effect of hunting. In all of these tabulations, the mean values of the exciting current and the line current are given. Also the mean values of the impressed E.M.F., which for a given excitation varied slightly, due to varying IR drop in the secondary leads mainly.

Phase	I_f	e_o	I	Osc.	D.C. Volts	e	Variation D.C. Volts	F
A	.63	70.0	58.0	113	70 - 77	38.0	7.0	1.88
"	.72	71.0	57.5	116	72 - 80	43.0	8.0	1.93
"	.78	71.0	58.0	118	72 - 80	45.6	8.0	1.97
B	.69	72.6	56.0	120	76 - 83	41.0	7.0	2.00
"	.71	73.0	56.0	121	76 - 83	42.0	7.0	2.02
"	.76	73.2	60.0	123	78 - 85	44.6	7.0	2.05

In order to determine what effect separate excitation would have upon the frequency of oscillation, the following readings were taken and plotted on sheet #5;-

Phase	I_f	Osc.	e	F
A & B	.65	165	39.0	2.75
"	.82	173	47.8	2.88
"	.90	178	51.7	2.97
"	1.00	182	56.5	3.04

An inspection of the curves on sheet #5 shows that for separate excitation the frequency of oscillation for a given value of excitation is five per cent less than with self-excitation.

While running the converter, self-excited, from the generator driven by engine #2, a peculiar movement of the ammeter needle showing the armature current was noticed. Combined with a rapid oscillation of small amplitude, there was a slow periodic swing over a much greater range. The frequency of both of these movements was counted. In such a case as this, the superposed frequencies can be found by dividing the number of nodes(same as slow swings) by two, and adding the quotient to, and subtracting

it from, the number of beats (same as small oscillations). A set of readings were taken, as follows:-

Phase	I_f	e	I	D.C. Volts	e	Variation D.C. Volts	Osc.
A	.67	75.0	47.0	96 - 99	40.0	3.0	160 & 42
B		"	54.0				
A	.72	"	47.2	97 - 99	43.0	2.0	164 & 33
B		"	54.2				
A	.77	"	46.7	97 - 99	45.0	2.0	168 & 26
B		"	53.7				
A	.79	"	47.2	96 - 98	46.2	2.0	170 & 22
B		"	54.2				
A	.81	"	47.2	96 - 98	47.5	2.0	172 & 18
B		"	53.7				

In the table below, an analysis is made of the observed frequencies of hunting just given, in the manner indicated above:-

I_f	Oscillations O_1	O_2	$\frac{O_2}{2}$	$O_1+\frac{O_2}{2}$	F_1	$O_1-\frac{O_2}{2}$	F_2
.67	160	42	21	181	3.02	139	2.32
.72	164	33	17	"	"	147	2.45
.77	168	26	13	"	"	155	2.59
.79	170	22	11	"	"	159	2.65
.81	172	18	9	"	"	163	2.72

Since one of the frequencies comes out a constant, this would point to source of hunting oscillation of constant frequency, that is, to engine hunting. Now 181 is approximately two-thirds of the speed that the engine is ordinarily run at, namely 265 R.P.M. And, as noted above, the engine has a marked irregularity every third revolution. Therefore, it would be reasonable to conclude that this component oscillation of constant frequency is due to the resultant action of engine irregularities occuring, one, of

small amplitude, each revolution, and another, of larger extent, every third revolution, of the engine.

The results above obtained are shown by the curves on sheet #8. On this sheet is also plotted a curve, also found on sheet #6, which is plotted from the values of $\underline{f_o}$ obtained by the use of the data in the first table given above (page 17) in the expression

$$f_o = \sqrt{\frac{f\ e\ e_o \sin(\alpha - \beta)}{4 \pi z\ M_o}}$$

It will be seen that the calculated values agree fairly well with the variable component of the observed frequency of hunting. This expression for hunting is supposed to hold only for small oscillations, and since the oscillations observed were of considerable amplitude, a closer agreement could not be expected. Then, too, the expression as given above probably does not express completely all of the factors entering into this case of hunting. And hence it is necessary to introduce a correction under the radical sign, in the shape of the term $- \frac{(c^2 + pP_o - h^2)}{64 \pi^2 M_o^2}$

There is present a magnetic lag of the converter field behind the resultant magnetomotive force, since the armature reaction varies in intensity and in phase during the considerable oscillation of β. And this magnetic lag is a cause for a term $\underline{h}^2$. If there be a cause for a term $\underline{h}^2$, then the machine oscillates with constantly increasing amplitude until it drops out of step or the energy losses, represented by $\underline{c}^2$ and $\underline{pP_o}$, stop the increase. Such would seem to be the action in the case of this machine.

The values of β in the expression were obtained from the "clock" diagram on sheet #7.

D.C. loads were put on the converter and no change in the frequency of hunting resulted.

-TESTS WITH ADDED MOMENTUM-

A 5-KW converter whose armature had a moment of inertia and radius of gyration the same as the armature of the machine under test, was placed with its shaft in line with the shaft of the 7.5-KW machine and the two were rigidly coupled together. The brushes were taken off the 5-KW machine, so that its effect was merely to add momentum to the armature of the other machine.

Then the performance of the machine was determined under these conditions, self-excited, and the excitation varied. The following table gives the data taken in this test:-

Phase	I_f	e_o	I	W	Osc.	e	F
A	.62	79.3	45.7	930	119	37.5	1.98
B		79.6	55.0	1050			
A	.80	80.2	48.0	750	125	46.7	2.08
B		80.2	56.0	1150			
A	.96	80.6	48.5	660	133	54.7	2.22
B		80.7	55.0	1250			
A	1.20	82.5	53.5	820	141	66.0	2.35
B		82.5	57.5	1320			

The values of I and f were plotted on sheet #5.

From the expression for hunting, f varies as $\sqrt{\frac{1}{M_o}}$, if the other factors remain constant. Let values of frequency for a certain field current, say .90 amperes, be read off the curves on sheet #5 representing the machine self-excited, running light, and driving the 5-KW machine. The frequencies are 3.09 and 2.16. Now the effect of coupling on the second machine was to double M_o. The frequency would then be changed in the ratio $= \sqrt{1/2}$ or .707.

Now the ratio of 2.16 to 3.09 is .700, or practically the same as the other. This coincidence of experimental with theoretical results goes to prove the applicability of the expression to this case of hunting.

With the same combination of machines, the 7.5-KW converter was separately excited and the readings below were taken:-

Phase	I_f	e_o	I	W	Osc.	e	F
A	.63	78.2	41.0	760	118	38.0	1.96
B		78.2	50.0	1000			
A	.70	78.0	41.5	820	120	41.6	2.00
B		78.3	49.5	920			
A	.82	79.7	37.5	780	124	48.0	2.06
B		80.0	46.0	880			
A	.90				126	51.6	2.10
B							
A	.99				128	56.2	2.14
B							
A	1.03	80.8	25.3	850	130	58.0	2.16
B		81.2	32.0				
A	1.07				130	60.0	2.16
B							
A	1.13				133	62.6	2.22
B							

These results were plotted on sheet #5. A comparison of this curve with that for self-excitation shows the effect of the separate excitation of the machine is to decrease the frequency of oscillation from that observed with self-excitation, the decrease varying from one per cent at the lowest excitation used to five per cent at the highest. It should also be noted that the current taken at the higher excitations is much below the current taken by the converter running alone. The decrease is fifty % for I_f = 1.03.

-TESTS WITH BELT DRIVE-

The machines as used in the preceding tests were uncoupled and a belt drive was arranged between them. The pulleys on both were of the same size, so that the driven machine revolved at the same speed as the converter. The mean mechanical momentum of the combination was 2 x 5680 = 11360 joules. The performance of the converter under various conditions is given below:-

Phase	I_f	e_o	I	D.C.	Volts D.C.	W	e	Variation D.C.Volts	Osc.
A	1.06	78.3	25.2	0	106 -107	-	59.6	1.0	104 & 72
B		77.5	28.7						
A	1.36	79.7	12.0	0	109 -110	400	72.5	1.0	104 & 72
B		79.0	18.0			660			
A	1.82	83.6	11.1	0	115 -116	-	90.0	1.0	104 & 72
B		83.0	12.7						
A	2.24	85.6	22.0	0	118 -119	-	103.0	1.0	104 & 72
B		84.2	22.7						
				Charging Storage Battery					
A	1.32	79.0	20.2	15amp.	105.5-107	-	71.0	1.5	104 & 72
B		78.4	25.3						
A	1.57	79.6	24.0	23amp.	106 - 108	-	80.9	2.0	104 & 72
B		78.9	28.2						
				Running On One Phase Alone					
A	.88	73.4	30.2	0	89.0-89.2	1200	50.5	.2	104
"	1.29	77.8	18.0	0	98.0-98.2	1150	69.7	.2	104
"	1.61	78.2	16.5	0	106.0- 6.2	1200	82.5	.2	104
"	2.17	81.8	41.7	0	121.5- 2.0	1370	101.0	.5	104
A	1.23	73.8	33.0	15amp.	94.5-95.0	2370	67.2	.5	104
B	1.29	78.6	20.2	0	104.0- 4.5	1000	69.7	.5	104
"	1.61	80.5	15.0	0	112.2- 2.5	1020	82.5	.3	104

An examination of the data on the preceding page shows the result of the belt drive to be

(1) A marked decrease in the amplitude of hunting. The minimum amplitude is obtained by the use of one phase alone. The following figures give a means of comparison of the amplitude of hunting under various conditions of operation:-

Condition of operation	Variation in D.C. Voltage
Converter alone, self-excited	2.0
" " " , one phase	7.0
" belted, " , no D.C. load	1.0
" " , " , 23 amp, D.C.	2.0
" " , " , phase A, minimum I	.2
" " , " , phase B, " "	.3
" " , " , phase A, " I, 15amp.	.5

(2) The frequency of hunting is constant, no matter what the excitation is. The ammeter needle shows two frequencies. The sum of these frequencies, 194 and 72, is 266, which is the speed of the engine. This fact would go to prove that the hunting with flexible belt drive is due to engine hunting alone, the belt drive suppressing the magnetic hunting.

(3) The current per phase is greatly reduced and brought down to nearly what it should be for correct operation.

The pulley used on the 5-KW machine in the above test was replaced by one of much greater diameter and weight and then the machines were belted together again. The mean mechanical momentum of this combination was calculated to be 7820 joules. The following data gives the performance of this combination:-

Phase	I_f	e_o	I	D.C.	Volts D.C.	e	Variation D.C. Volts	Osc.
A	1.11	79.0	20.5	0	107.3	62.0	.2	232 & 34
B		78.2	24.0		107.5			
A	1.78	81.5	6.0	0	112.2	89.0	.3	232 & 34
B		81.4	7.5		112.5			
A	2.37	85.0	25.5	0	117.0	106.5	.5	232 & 34
B		83.5	26.5		117.5			
A	1.48	79.5	22.7	25amp.	106.0	78.0	1.0	232 & 34
B		77.6	24.7		107.0			
				Running On One Phase Alone				
B	1.62	78.5	10.2	0	109.0 109.1	82.5	.1	232 & 34

The results above show a still further reduction of the amplitude of hunting. In fact, the oscillations were almost eliminated. As was the case when the other pulley was used, the taking of direct current from the converter increased the amplitude of the oscillations. And the amplitude of oscillation was less when the machine ran on one phase than when both phases were in use. The minimum current taken when running on both phases was in this case 6.0 amperes, and when the small pulley was used, 11.1 amperes, showing a decrease of nearly fifty per cent in current consumption. The frequency of hunting remained constant through the test, but it was greater than the frequency observed in the preceding test. However, the sum of the two frequencies in this case is the same as in the other, that is, 232+34 = 194+72 = 266, the R.P.M. of the engine. This coincidence seems to prove that the hunting oscillations in the case of flexible belt drive of an additional momentum are due to engine pulsations.

-TESTS WITH DAMPERS-

The pole-faces of the converter were faced with copper plate one-sixteenth of an inch thick, fastened in place by screws. Then a test was run on the machine, with the following results:-

Phase	I_f	e_o	I	D.C.	W	e	Osc.
A	1.02	78.0	21.5	0	1240	57.6	270
B		78.0	31.0		1670		
A	1.54	84.7	18.7	0	1500	80.0	265
B		84.7	25.0		1950		

The dampers effectually eliminated all hunting except a very small oscillation which, as nearly as could be determined by such rapid counting, had the frequency as given above. This frequency, it will be noted, is practically the engine speed, indicating that the engine hunting was not entirely suppressed.

The current per phase as given above is very materially less than the current without the dampers.

Although the dampers practically eliminated the hunting, the energy losses in them were so great as to heat them rapidly, and the machine would run only a short time before it would have to be shut down on account of the dangerously high temperature of the whole machine. Therefore the dampers were removed. Possibly a more efficient damper of the squirrel-cage type would be effectual here, but this is open to question.

The power required to force the magnetic flux of the machine thru the circuits of the damping device was calculated from readings of power input to a motor driving the converter at synchronous speed. The final results follow:-

I_f =.62, e = 37.5, W = 1000 I_f =.80, e = 46.7, W = 1250

-SAMPLE CALCULATION OF FREQUENCY OF HUNTING-

$$f_o = \sqrt{\frac{f\ e\ e_o \sin(\alpha - \beta)}{4 \pi z M_o}}$$

Data:-

f = 60 cycles per second.

e = 35.3 volts, corresponding to excitation of .8 amp.

e_o = 77.5 " impressed upon phase A.

α = 82° (see clock diagram on sheet #7).

β = 12° (from " " " " ").

z = .876 ohms, synchronous impedance of machine.

M_o = 2840 joules (see calculation below).

Then $$f_o = \sqrt{\frac{60 \times 35.3 \times 77.5 \times \sin 70^\circ}{4 \times \pi \times .876 \times 2840}}$$

$$= \sqrt{\frac{60 \times 35.3 \times 77.5 \times .939}{4 \times \pi \times .876 \times 2840}}$$

= 2.33 oscillations per second.

Calculation of M_o:-

$M_o = \frac{1}{2} m v_o^2$, where m is the mass of the rotating part of the machine, = 4.83 g-lbs, and v_o is the velocity in feet per second at radius of gyration, = .221 ft. R.P.M. = 1800.

$$v = 2 \times \pi \times .221 \times \frac{1800}{60} = 41.65 \text{ feet per second.}$$

$$M = \frac{1}{2} \times 4.83 \times (41.65)^2 \times 1.356$$

$$= 5680 \text{ joules.}$$

The above expression was deduced for one phase. In this machine, there are two phases acting upon the armature, so the value of M_o just found is divided by two to give a value for use in the expression for f_o. This gives 2840 joules.

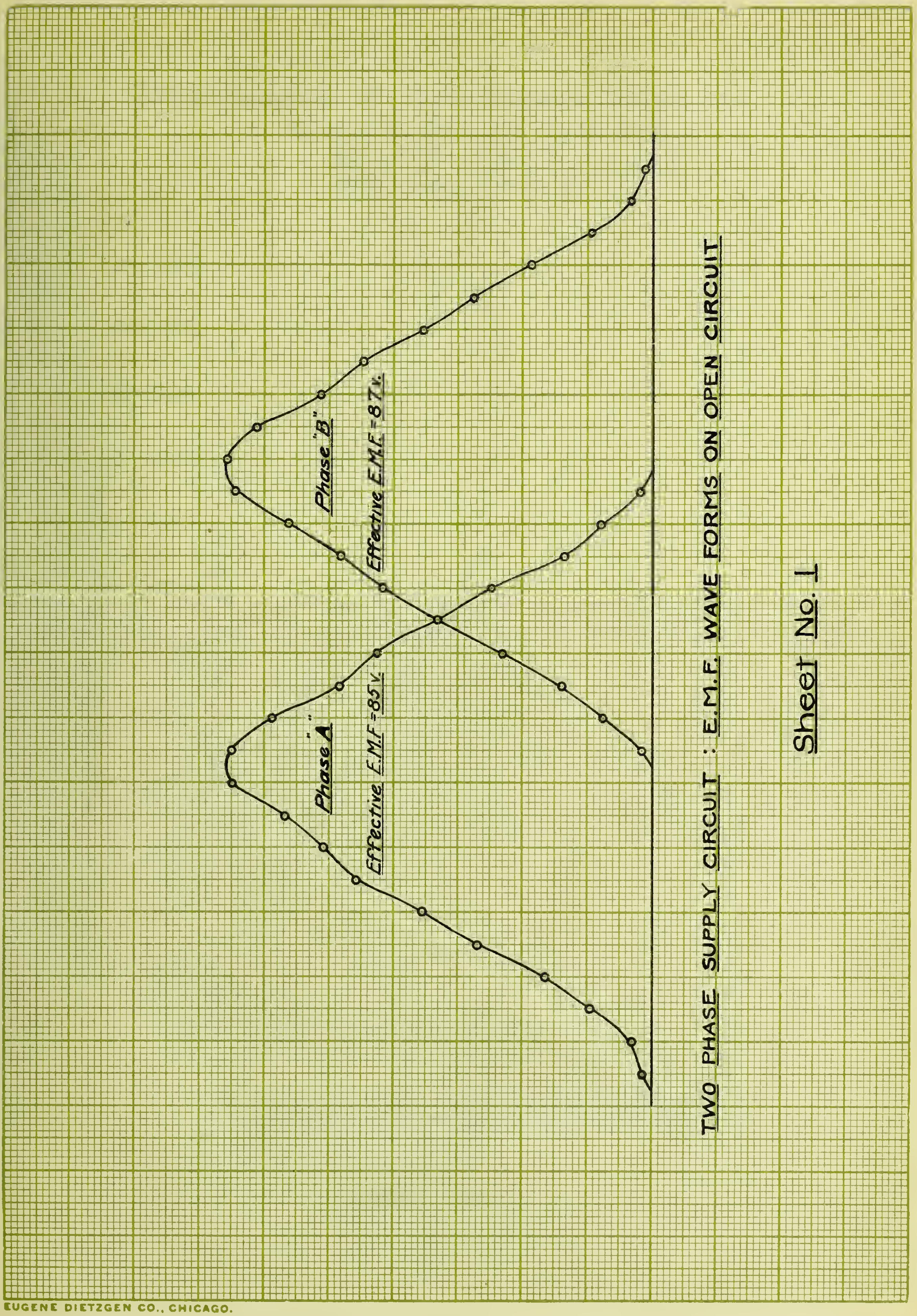
This assumption in regard to taking one-half of M_o is substantiated by experimental results. The same value of f_o would be obtained if the whole of M_o were used in the formula and then the result were multiplied by 1.414 (= $\sqrt{2}$). On sheet #6 are two curves giving the frequencies observed when the machine is run separately from each phase, and also a curve giving the frequency when both phases were in service. If, now, the mean of the frequencies for a given excitation be calculated from the first two curves named above , and the result multiplied by 1.414, the resulting frequency approximates the frequency shown on the third curve for the same excitation. And if a correction be made for the lower impressed voltage when the phases are used separately, the calculated and the observed values practically coincide. So it is fair to assume that the calculated frequency of hunting if two phases be used is given by using one-half of the total mean mechanical momentum in the formula.

-CONCLUSIONS-

In this special case of rotary converter hunting, there is present engine hunting aggravated by excessive hunting due to magnetic lag. The hunting is reduced by separate excitation, by coupling on rigidly an additional momentum, by belt drive of an additional momentum, or by the use of dampers. Of these methods, the flexible belt drive seems to be most efficient from the standpoint of effectiveness and minimum consumption of energy. But at best these devices are hardly a good commercial proposition, and the production of direct current would be much better secured by an induction motor-generator set.

The frequency of hunting as calculated from Steinmetz' formula agree fairly well with the frequency due to magnetic hunting. The discrepancy between the two would appear to be due (1) to the fact that the formula considers only small oscillations and the oscillations observed were rather large, and (2) to the presence of other factors affecting the hunting other than those considered in the simple formula.

The frequency of hunting was also calculated from a consideration of the entire circuit; generator, primary line, transformer, secondary leads, and converter. All of the elements of the secondary circuit were expressed in primary terms by multiplying by the square of the transformer ratio, 23 : 1, and the resistance and reactance of the equivalent transformer were calculated. Of course, the counter E.M.F. of the converter was simply multiplied by 23 to express it in primary terms. It was found that the results were substantially the same as those already discussed . The impedance term was largely composed of the impedance derived from the synchronous impedance of the converter, showing that the impedance of the converter determines in large measure the frequency of oscillation. If the converter had a greater impedance, the frequency of oscillation would be less, as the impedance enters into the denominator of the expression for hunting.

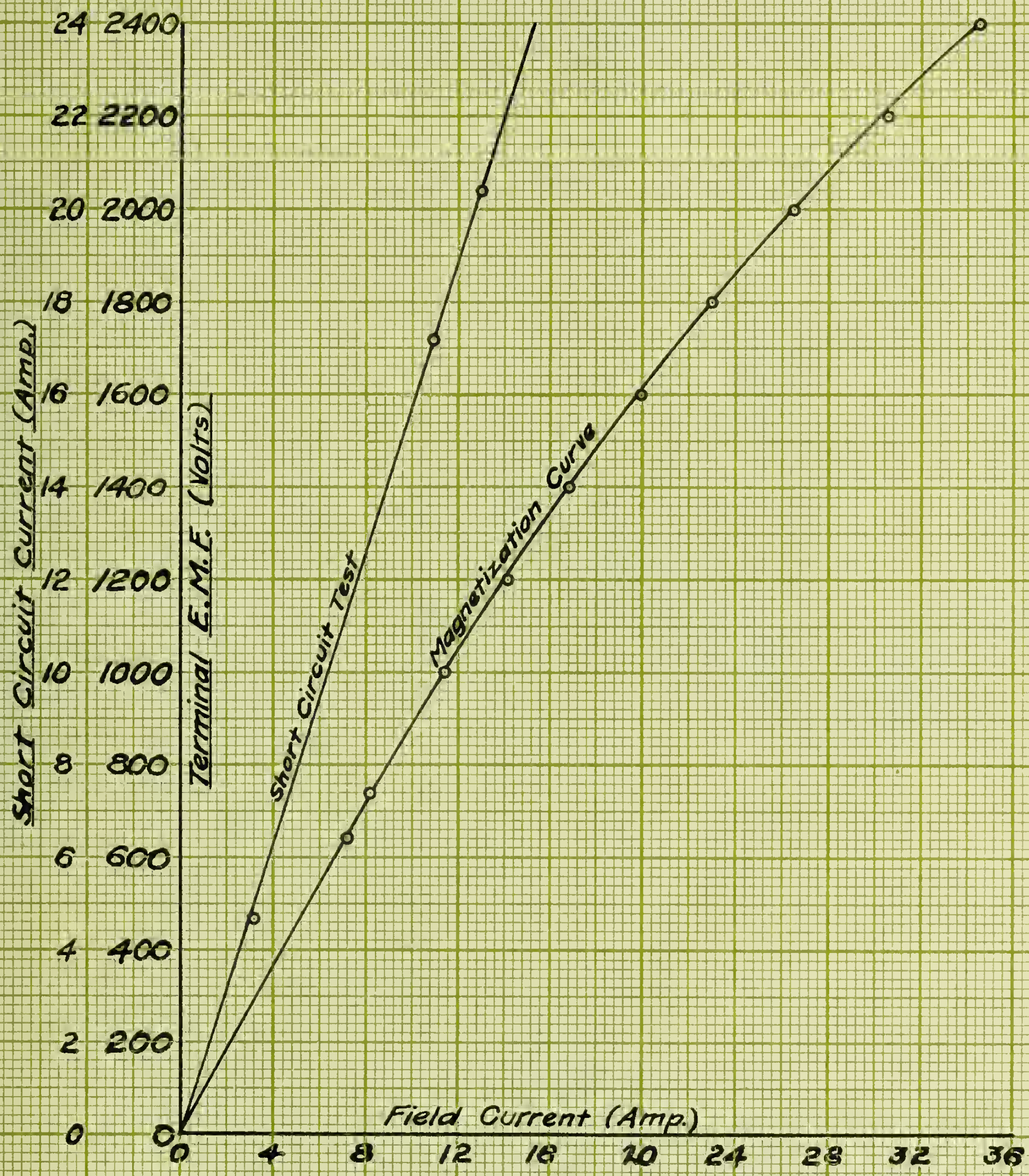


TWO PHASE SUPPLY CIRCUIT : E.M.F. WAVE FORMS ON OPEN CIRCUIT

Sheet No. 1

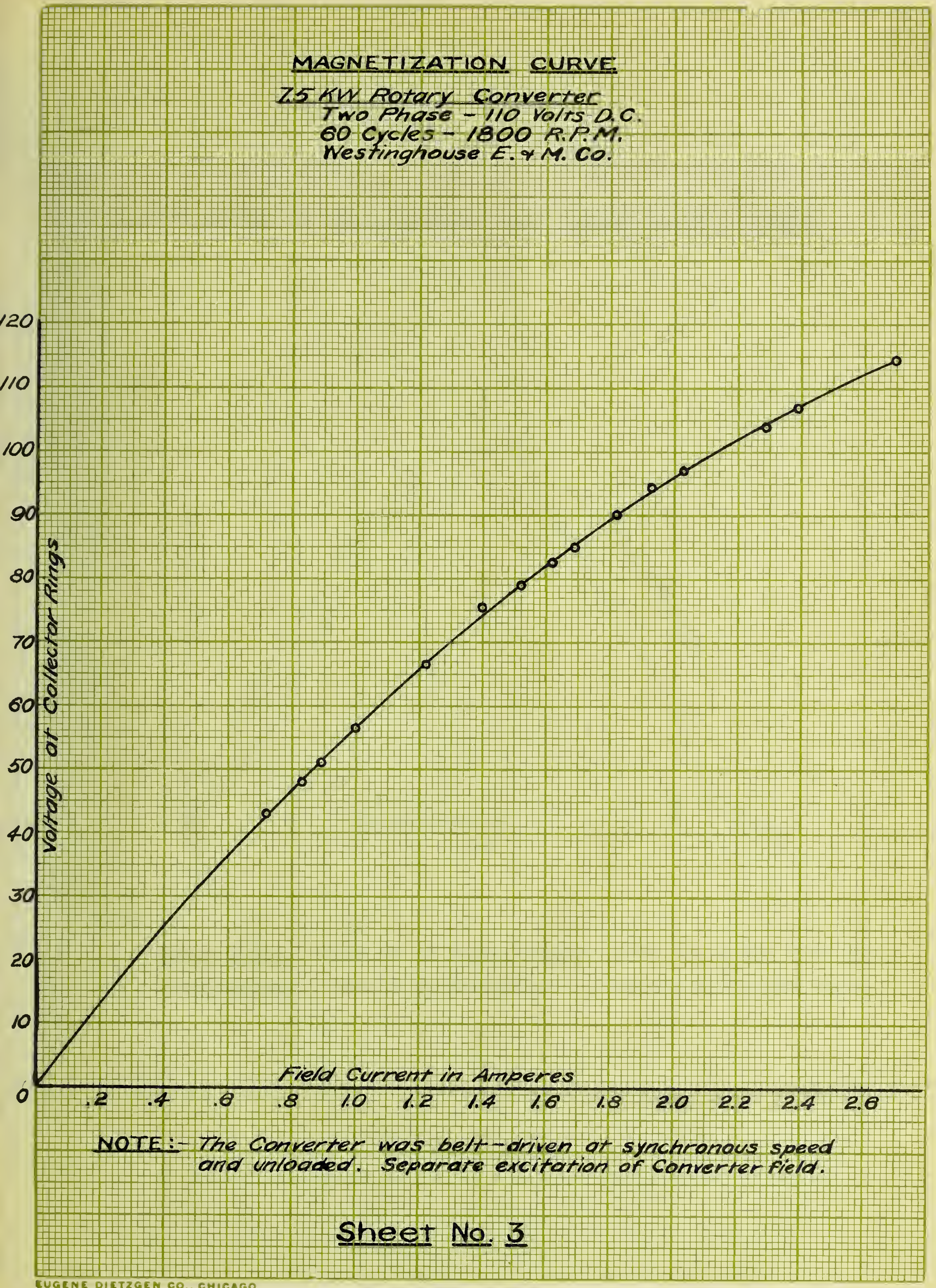
Determination of Synchronous Impedance

General Electric A.C. Generator
Type AQB - Form E
Class 28 - 105 A - 257 R.P.M.
Volts 2300 - Amp. 23

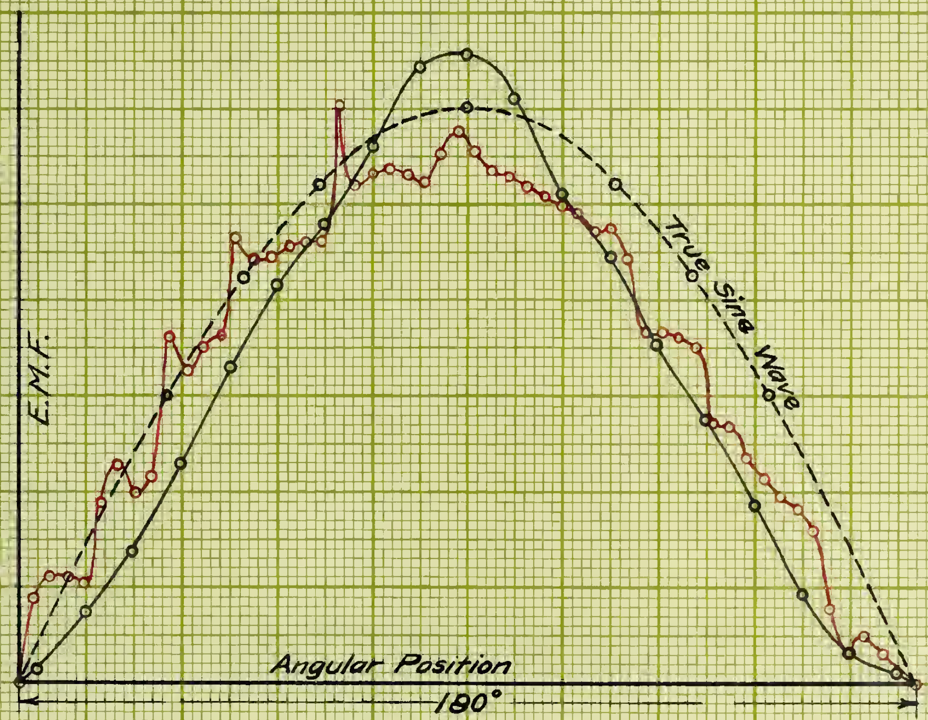


The Synchronous Impedance for the light loads used by the Rotary Converter is sensibly constant and amounts to 57 Ohms.

Sheet No. 2


MAGNETIZATION CURVE.
7.5 KW Rotary Converter
Two Phase - 110 Volts D.C.
60 Cycles - 1800 R.P.M.
Westinghouse E. & M. Co.
Voltage at Collector Rings
120
110
100
90
80
70
60
50
40
30
20
10
0
Field Current in Amperes
.2
.4
.6
.8
1.0
1.2
1.4
1.6
1.8
2.0
2.2
2.4
2.6
NOTE:- The Converter was belt-driven at synchronous speed and unloaded. Separate excitation of Converter field.
Sheet No. 3
EUGENE DIETZGEN CO., CHICAGO.

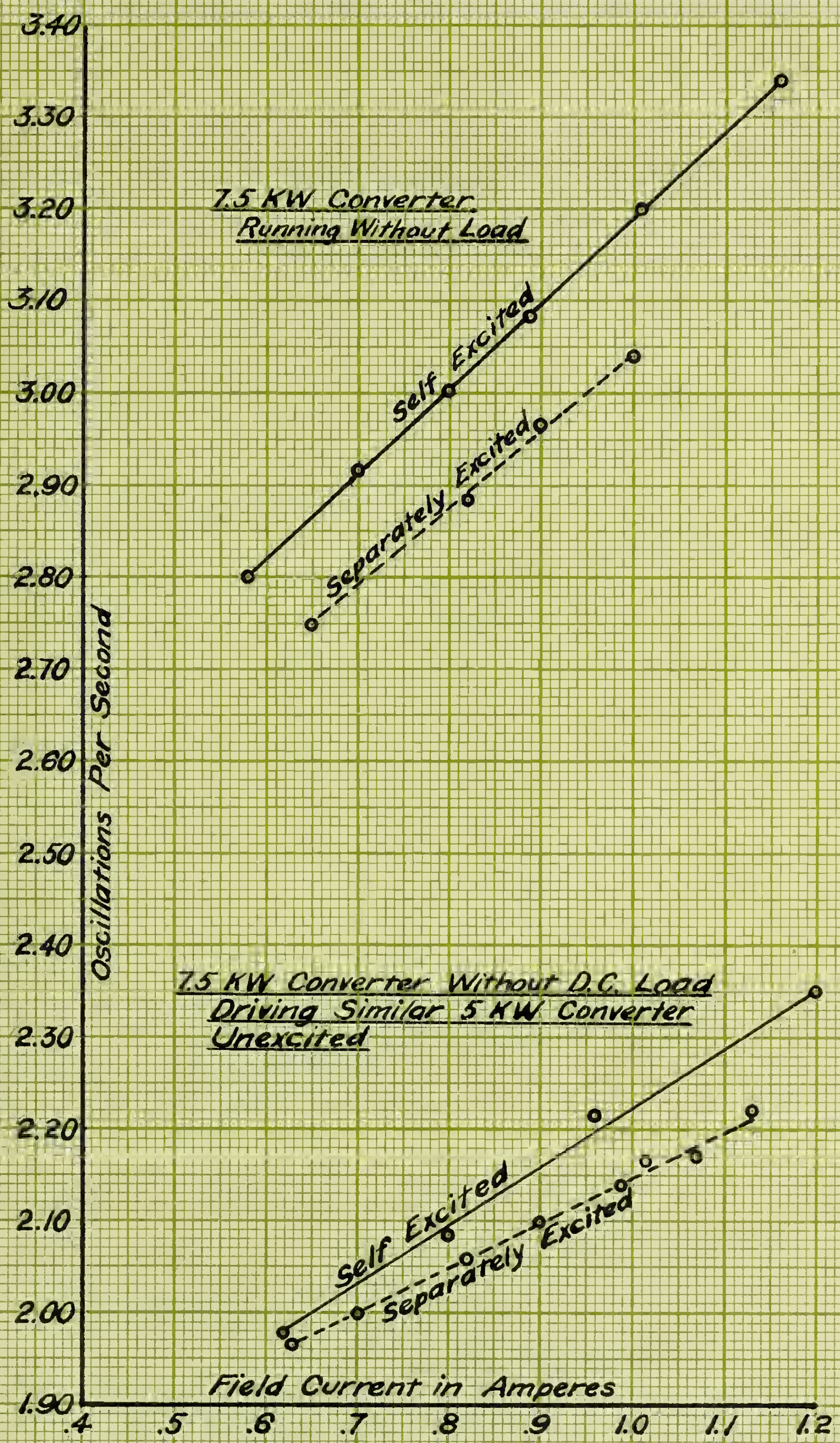
COMPARISON OF ELECTROMOTIVE FORCE WAVE FORMS



Black Curve : Phase "B" of Supply Circuit. Effective E.M.F. = 87 volts.
Red Curve : Phase "B" of Converter. Effective E.M.F. = 86 volts.

Sheet No. 4

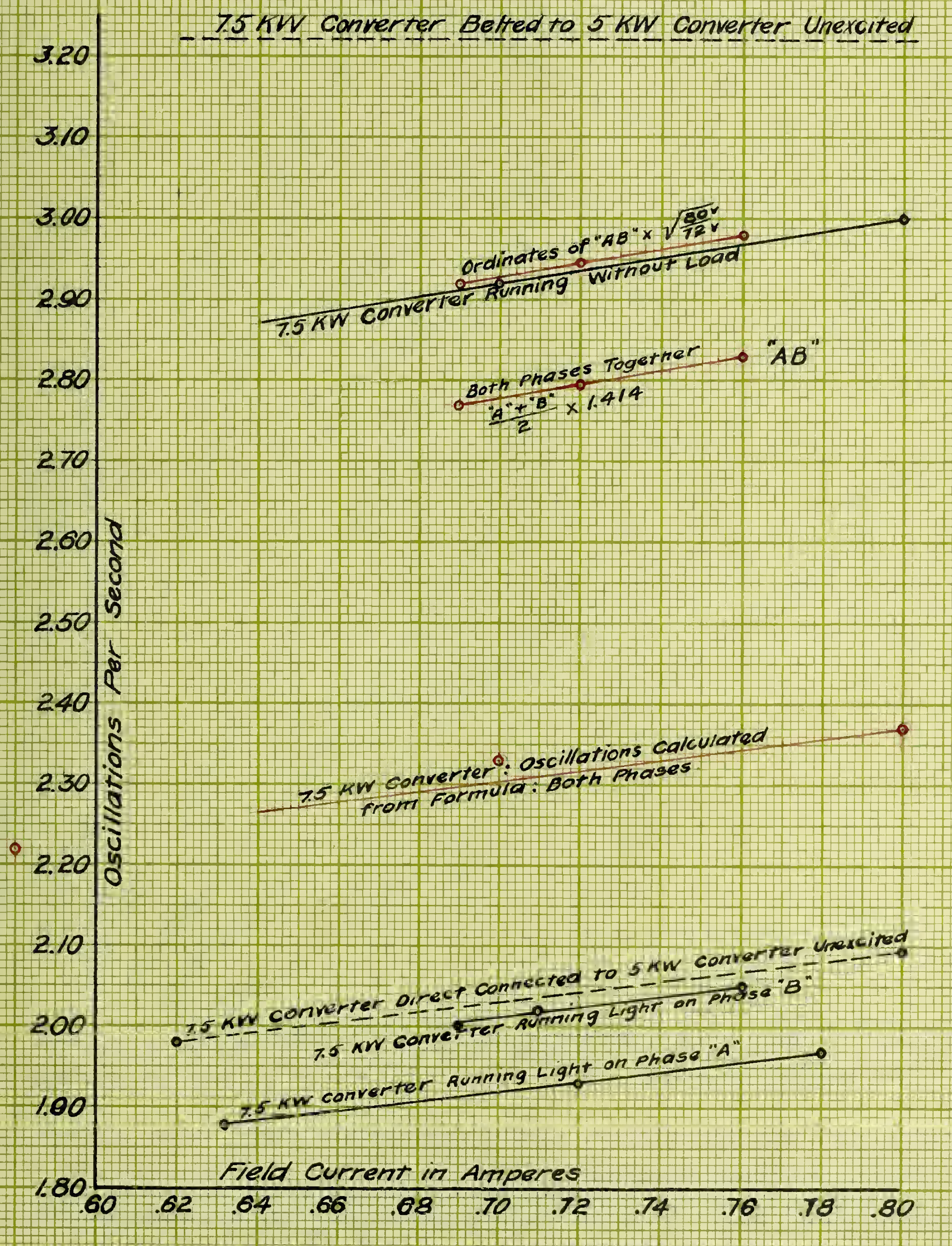
CURVES GIVING FREQUENCY OF HUNTING OSCILLATIONS
OF ROTARY CONVERTER UNDER VARIOUS CONDITIONS



NOTE: When 7.5 KW Machine Drives 5 KW, The Moment of Inertia of the Rotating Element is Exactly Twice the Moment of Inertia of the Armature of the 7.5 KW Machine alone

Sheet No. 5

CURVES GIVING FREQUENCY OF HUNTING OSCILLATIONS OF ROTARY CONVERTER UNDER VARIOUS CONDITIONS

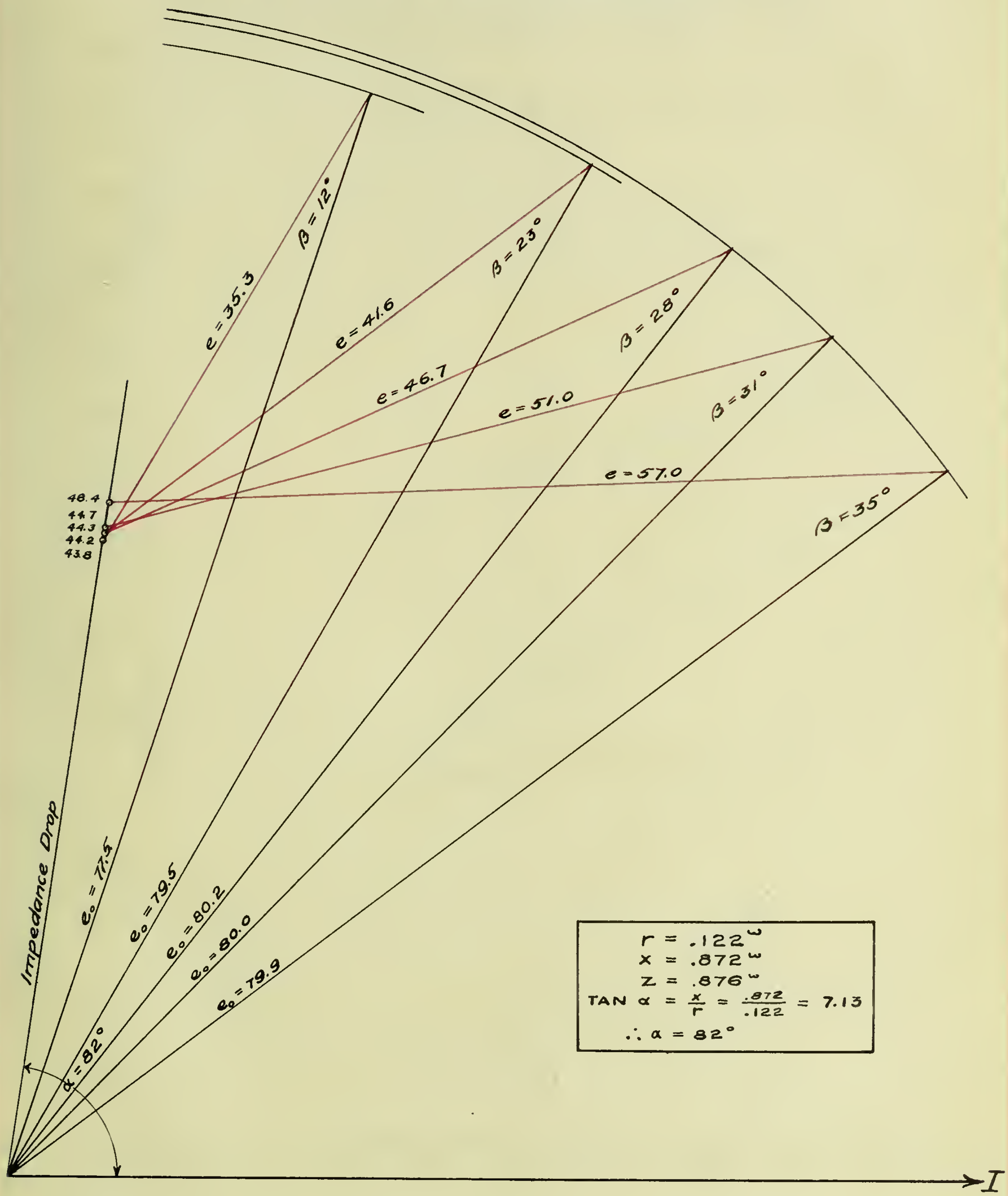


Black Curves give results from experiment
Red Curves are calculated

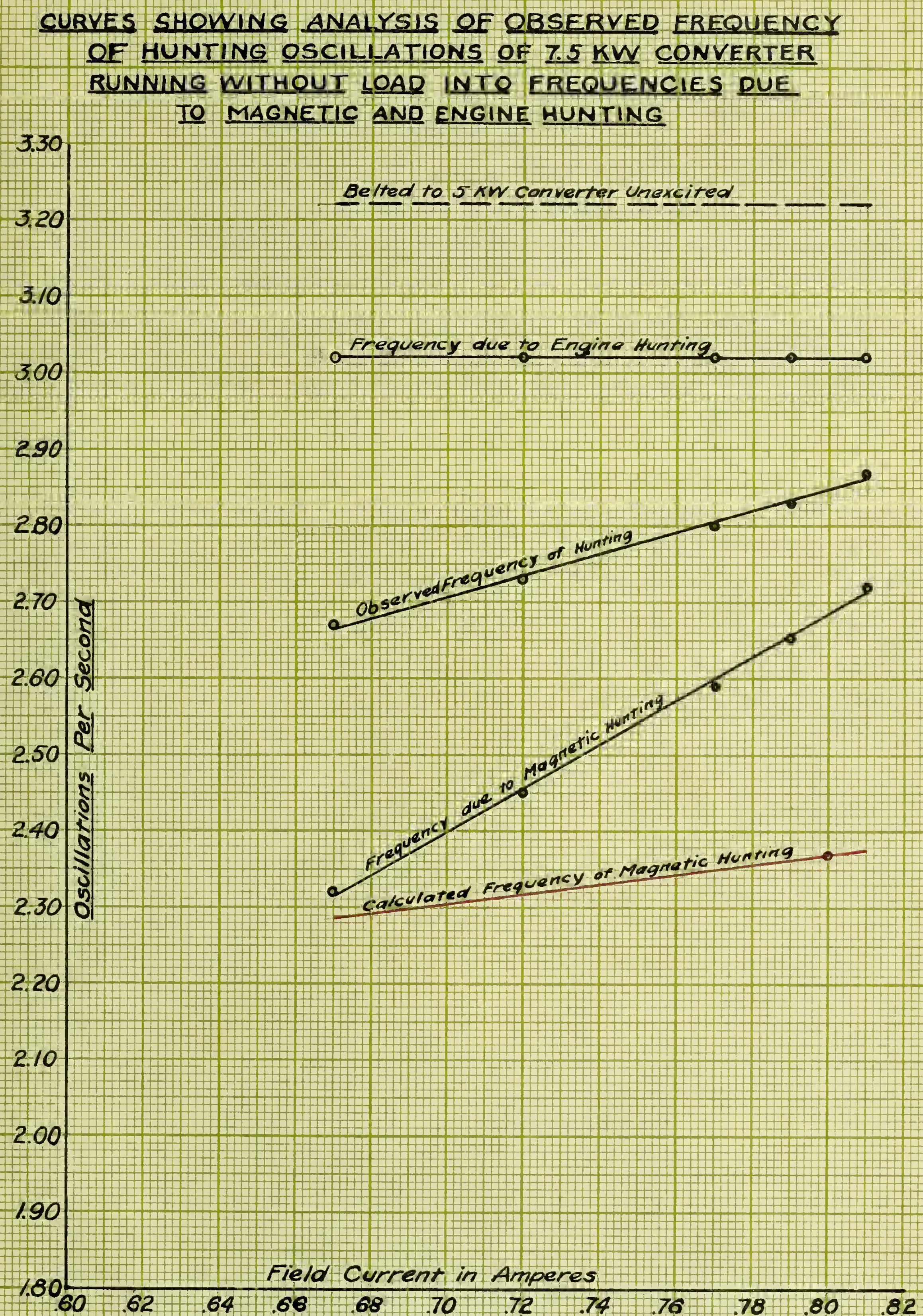
Sheet No. 6

CLOCK DIAGRAM

7.5 KW CONVERTER RUNNING WITHOUT LOAD
SELF-EXCITED : EXCITATION VARIED



Sheet No. 7


CURVES SHOWING ANALYSIS OF OBSERVED FREQUENCY OF HUNTING OSCILLATIONS OF 7.5 KW CONVERTER RUNNING WITHOUT LOAD INTO FREQUENCIES DUE TO MAGNETIC AND ENGINE HUNTING
Belted to 5 KW Converter Unexcited
Frequency due to Engine Hunting
Observed Frequency of Hunting
Frequency due to Magnetic Hunting
Calculated Frequency of Magnetic Hunting
Oscillations Per Second
Field Current in Amperes
3.30
3.20
3.10
3.00
2.90
2.80
2.70
2.60
2.50
2.40
2.30
2.20
2.10
2.00
1.90
1.80
.60
.62
.64
.66
.68
.70
.72
.74
.76
.78
.80
.82

Sheet No. 8